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14. ABSTRACT

Future tactical networks will be complex, with severe constraints on energy and bandwidth, operating in dynamic and unpredictable environments. By exploiting the broadcast nature of the wireless medium and spatially dispersed nodes, some of the advantages of using multiple antennas can be realized through cooperation among nodes in a network. Recent work has demonstrated that cooperation can provide increased range, improved efficiency, and more reliable and longer lasting connectivity. However, in large, complex networks, centralized control will likely be infeasible, and the overhead required for communications between the cooperating nodes could be excessive. To address these issues, we focused on developing and analyzing cooperative strategies which work well without centralized control or inter-node communications, and which are based on locally obtained information. In particular, we devised several decentralized techniques for relay selection and combining, as well as for power allocation, and demonstrated the efficacy of these approaches. We also studied the use of OFDM to facilitate cooperation in the extension of these strategies to multihop networks. In addition, to further understand the costs of using cooperation and to facilitate their future real

15. SUBJECT TERMS

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Final Report
Cooperative Networking

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1. Introduction

Future tactical networks will be complex, with severe constraints on energy and bandwidth, operating in dynamic and unpredictable environments. The use of multiple antennas, which has provided significant improvements in performance for single-link communications, should also provide similar advantages in such networks. By exploiting the broadcast nature of the wireless medium and spatially dispersed nodes, some of these advantages can be realized through cooperation among single-antenna nodes in a network.

In cooperative systems, a group of nodes can transmit together as a virtual antenna array to obtain diversity gains. Recent work has demonstrated that cooperation can significantly improve the performance of wireless networks; in particular, cooperation can provide increased transmission range, improved energy and bandwidth efficiency, and more reliable and longer lasting network connectivity. However, in large, complex, dynamic networks, centralized control will likely be infeasible, and the overhead required for communications between the cooperating nodes could be excessive. To address these issues, we focused on developing and analyzing cooperative strategies which work well without centralized control or full inter-node communications, and which are based as much as possible on locally obtained information.

Much of this previous work also focuses on the physical-layer capabilities of cooperation in static, idealized scenarios, ignoring both the overheads that may be incurred in a networking context and the interactions with higher layer protocols. These costs are actually significant enough that the net gain of using cooperation in a networking context remains uncertain. Moreover, even if these costs appear small in simple network scenarios, they will increase significantly in large, complex, dynamic environments. To further understand the costs of using cooperation in wireless networks and to facilitate their future realization, we collaborated with Prof. C.-C. Shen (Delaware) on a realistic evaluation of cooperation in a networking context.

2. Objectives

This research program was aimed at developing a broad suite of cooperative strategies that can provide reliable network performance in highly dynamic environments, with severe constraints on energy and bandwidth. The original program proposal included the following goals:

- Development of cooperative strategies with different amounts of local information. A major goal was to devise algorithms based as much as possible on locally obtained information. This includes strategies for relay selection and combining, as well as for power allocation and routing.

- Evaluation of the proposed cooperative schemes in the presence of practical issues such as synchronization errors and interference, and for a variety of performance metrics relevant to large networks including outage, throughput, connectivity, link failure, and delay.
- Development of OFDM- and OFDMA-based resource allocation strategies for single-source, as well as multiple-source, cooperative transmission. This includes the evaluation of different resource allocation algorithms, with varying levels of channel state information (CSI) available, under realistic propagation conditions and for different network configurations.
- Development of OFDMA-based routing in multihop networks. This includes determining the required flow of CSI throughout the network, and quantifying the effects of interference.
- Design and evaluation (in a networking context) of cross-layer protocols that incorporate cooperation, taking into account the overheads incurred at the physical, MAC, and network layers. The goal here is to minimize node communications, for both multihop networks and networks with multiple simultaneous data flows.

3. *Summary of Research Results*

In this work, we devised several decentralized cooperative techniques for relay selection and combining, as well as for power allocation, and, through analysis and simulation, have demonstrated the efficacy of these approaches. We have also studied the use of OFDM to facilitate cooperation in the extension of these strategies to multihop networks. The results and accomplishments from the work supported by this grant are summarized below; detailed descriptions can be found in the publications listed in Section 5 (hyperlinks to the papers are included). The work has culminated in fourteen conference papers, as well as five journal articles and two dissertations (and another in preparation). We have also prepared four manuscripts for submission to the *IEEE Transactions on Wireless Communications*. To better organize the discussion of the results, the work has been divided into three categories with several sub-categories.

A. Decentralized Distributed Cooperative Techniques

Decentralized Relay-Selection and Transmission

We developed cooperative schemes that work well even without a central control unit or full inter-node communications. We considered several distributed space-time block coding (Dis-STBC) schemes in a two-stage, decode-and-forward (DF), relay network. In particular, for a single source-destination pair, we considered a pre-assignment scheme and two randomized transmission techniques. The average diversity order was analyzed, and the end-to-end outage performance was evaluated under realistic channel conditions and with varying network configurations. In addition, some rules for optimizing the code design have been presented. Simulation results show that, for any given number of columns in the underlying STBC matrix, the optimized discrete randomized schemes can achieve almost the same performance as the continuous randomized scheme, as long as the number of potential relays is much larger than the number of columns. Finally, we developed an effective Dis-STBC approach when there are multiple active sources that have a common destination.

Power-Efficient Relay Selection

We devised a power-efficient, relay-selection strategy for decentralized Dis-STBC, which could be applied to either two-hop or multihop DF networks. In this strategy, only a small amount of local

information is required to optimize the relay selection at each hop. The advantage of the proposed strategy was demonstrated through asymptotic outage analyses, as well as through simulations.

Power Allocation

We developed two ad-hoc, yet efficient, power-allocation strategies for decentralized Dis-STBC. The first strategy requires some control information and is near-optimal; the second strategy requires no control signaling, but is sub-optimal. Asymptotic outage analyses and the simulations for outage and link-failure probability illustrate the power-efficiency advantages of these strategies over a constant-power allocation (i.e., where all of the relays transmit the same power).

Network Lifetime

We considered a two-stage relay network in which one source and one selected relay cooperate to transmit source messages to the destination. When a Best-Select strategy is used, the forwarding relay is selected as the node which has the best instantaneous or mean channel gain to the destination; for this strategy, since the relay nodes with good channel gains will drain their energy budget rapidly, the network lifetime is small and the quality of service at the destination will degrade with time. To maximize the network lifetime while incurring the minimum overhead, we proposed an efficient relay-selection strategy using only the mean CSI and the residual energy information. A decentralized implementation with minimal overhead was also proposed. The asymptotic performance analyses and simulations showed that, for any given transmit power level of each node, the proposed strategy can maximize the network lifetime while achieving much more stable outage performance than the conventional mean-CSI-based Best-Select strategy.

Network Coding for Cooperation with Multiple Source-Destination Pairs

We proposed an efficient cooperative network-coding scheme for a two-stage DF cooperative network with multiple source-destination pairs. In particular, using mean-CSI-based, Best-Select cooperation, the selected best relay performs network coding on the correctly decoded information from all the sources by transmitting a random linear combination of the columns in an underlying full-rate, full-diversity, perfect STBC. A decentralized implementation with minimal overhead was also presented. Under realistic conditions, including the effects of path-loss and flat Rayleigh fading, the performance in terms of the single-pair outage probability was evaluated. Simulation results show that, when compared with both non-cooperative direct transmission and serial cooperative re-transmission, the proposed cooperative network-coding scheme can achieve much better outage performance while also achieving full-rate re-transmission for each single source-destination pair.

Hop-by-Hop Routing Using Mean Channel Gains

We developed an optimized hop-by-hop routing strategy for multihop, DF cooperative networks when only knowledge about the mean channel gains is available. In particular, a novel optimization metric was proposed to select the best relay on a per-hop basis by only utilizing the local mean channel gain of the current hop. The end-to-end outage performance was evaluated; the proposed hop-by-hop routing can provide a good trade-off between performance and overhead.

Cooperative Routing

We addressed the routing issue from a link-layer point of view. We focused on a multihop network with multiple relays at each hop, and three routing strategies were designed to achieve the full

diversity gain provided by the cooperation among relays. In particular, an optimal routing strategy was proposed to minimize the end-to-end outage, which requires the instantaneous CSI of all the links and serves as a performance bound. An ad-hoc routing strategy was also proposed based on a hop-by-hop relay selection, which can be easily implemented in a distributed way. To achieve a good complexity-performance tradeoff, an N-hop routing strategy was further proposed, where a joint optimization is performed every N hops. For broadband transmission, a link-quality metric was first proposed to measure broadband links; then, the three routing strategies that were proposed for the flat fading scenarios were re-designed to achieve cooperative and frequency-diversity gain. The outage analysis and simulation results showed that all three protocols can achieve full diversity gain. The outage of optimal routing remains constant with an increase in the number of hops, M, and the outage of ad-hoc routing increases linearly; N-hop routing, where a joint optimization is performed every N hops, can achieve a good complexity-performance tradeoff.

Fairness and Cooperation

We developed a price-aware multiuser cooperation protocol, demonstrated how to efficiently and fairly allocate resources among multiple users and their relays, and showed that, in energy-constrained cooperative ad-hoc networks, fairness can actually bring significant throughput gains. In order to further improve the fairness, we proposed a price-aware cooperation protocol, where the residual energy information of each node is exploited to shape the relay set. Simulation results showed that by using this price lever, fairness can be significantly improved. This benefit turns out to bring much higher throughput than the traditional direct transmission and full cooperation schemes.

B. OFDM-Based Cooperation

Relay and Subchannel Assignment and Combining

We investigated the use of OFDM to facilitate cooperation among relays in a wireless network. In particular, we considered different relay and subchannel assignment and combining schemes. Based on the amount of CSI, resources, such as subchannels, can be allocated to relays to improve the end-to-end performance. Simulation results were provided to compare the performance of these schemes in terms of block error rate, and it was shown that significant performance gains can be obtained even with little CSI at the relays.

Resource Allocation for OFDM/OFDMA Relaying

We investigated the resource allocation problem for an OFDM cooperative network with a single source-destination pair and multiple relays. Selective OFDMA relaying, where the relay selection is performed in a per-subcarrier manner, and selective OFDM relaying, where one best relay is selected to relay the entire OFDM block, were compared in a two-hop random network. The outage analysis clearly shows that full spatial diversity gain can be achieved with Selective OFDMA Relaying; in contrast, no diversity gain can be obtained if the entire OFDM block chooses the same relay with the highest combined SNR.

Also, assuming knowledge of the instantaneous channel gains for all links in the entire network, we proposed several bit and power allocation schemes aiming at minimizing the total transmission power under a target rate constraint. First, an optimal and efficient bit-loading algorithm was proposed when the relay node uses the same subchannel to relay the information transmitted by the source node. To further improve the performance gain, subchannel permutation, in which the

subchannels are reallocated at the relays, was considered. An optimal permutation algorithm was first proposed and then an efficient sub-optimal algorithm was considered to achieve a better complexity-performance tradeoff. A distributed bit-loading algorithm was also proposed for ad-hoc networks. Simulation results showed that significant performance gains can be achieved by the proposed bit loading algorithms, especially when subchannel permutation is employed.

We also investigated the resource allocation problem for an OFDMA cooperative network with multiple source-destination pairs and multiple assisting relays. Specifically, two subchannel permutation algorithms, amplitude-craving greedy with subchannel permutation (ACGSP) and joint subchannel allocation and subchannel permutation (JSASP), were proposed. Simulation results showed that the simple ACGSP algorithm can further improve the performance by at least 2 dB. The JSASP algorithm performs a little better than ACGSP at the expense of computational complexity. A decentralized algorithm was also considered, and simulations demonstrated its good performance.

C. Cooperation in a Networking Context

In collaboration with Prof. C.-C. Shen, CIS, University of Delaware, we investigated the performance, and hence the benefits, of incorporating cooperative communications in realistic networking scenarios by taking into account the overheads incurred at the physical, MAC, and network layers. Initially, we focused on a cooperative network using decentralized Dis-STBC and considered only a few sources of overhead. Specifically, we modified the physical-layer model of the QualNet simulator to incorporate decentralized Dis-STBC into all SINR calculations and to combine signals concurrently transmitted from multiple relays. At the MAC layer, we implemented a path-centric scheme which reserves a multihop path between the source and destination, facilitates relay selection, and coordinates cooperation. At the network layer, we modified the standard Dynamic Source Routing protocol so that the source route is provided to the MAC for path reservation. Networking performance was then evaluated for scenarios with multiple simultaneous data flows, and compared with non-cooperative communication. Simulation results demonstrated that significant performance improvement can be achieved by employing cooperation. Studying these mechanisms allowed us to measure the cost in terms of bandwidth and energy consumption of the additional coordination required for cooperation, and to identify several significant "hidden" costs that were either not expected to impact the performance of cooperative communications or have been ignored in previous work.

4. Personnel Supported

Prof. Leonard J. Cimini, Jr. (Principal Investigator)
Dr. Lin Dai (Research Fellow, now at the City University of Hong Kong) – Supported in 2006
Dr. Bo Gui (Research Assistant, now at Cisco Systems, Inc.) – Ph.D. granted Fall 2008
Lu Zhang (Research Assistant) – Ph.D. expected Spring 2009
Justin Yackoski (Research Assistant, Dr. C.-C. Shen) – Ph.D. expected Spring 2009 – Provided travel support through this grant

5. Technical Publications

A. Conference Papers

[1] B. Gui, L. J. Cimini, Jr., and L. Dai, "OFDM for cooperative networking with limited channel state information," in *Proc. of Milcom'06*.
http://www.eecis.udel.edu/~bgui/Milcom06.pdf

[2] L. Zhang, L. J. Cimini, Jr., L. Dai, and X.-G. Xia, "Relaying strategies for cooperative networks with minimal node cooperation," in *Proc. of Milcom'06*.
http://www.eecis.udel.edu/~lzhang/Milcom2006RevisedFinal.pdf

[3] B. Gui, L. Dai, and L. J. Cimini, Jr., "Routing strategies in broadband multihop cooperative networks," in *Proc. of CISS'07*.
http://www.eecis.udel.edu/~bgui/CISS07.pdf

[4] L. Zhang and L. J. Cimini, Jr., "Power-efficient relay selection for decentralized distributed space-time block coding," in *Proc. of CISS'07*.
http://www.eecis.udel.edu/~lzhang/CISS2007Final.pdf

[5] L. Dai, B. Gui, and L. J. Cimini, Jr., "Selective relaying in OFDM multihop cooperative networks," in *Proc. of WCNC'07*.
http://www.eecis.udel.edu/~bgui/WCNC07_LIN.pdf

[6] B. Gui, L. Dai, and L. J. Cimini, Jr., "Routing strategies in multihop cooperative networks," in *Proc. of WCNC'07*.
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[10] B. Gui, and L. J. Cimini, Jr., "Resource allocation algorithms for multiuser cooperative OFDMA systems with subchannel permutation," in *Proc. of CISS'08*.
http://www.eecis.udel.edu/~bgui/CISS08_BO.pdf

[11] L. Zhang and L. J. Cimini, Jr., "Cooperative network coding in selective decode-and-forward networks with multiple source-destination pairs," in *Proc. of CISS'08*.
http://www.eecis.udel.edu/~lzhang/CISS2008Final.pdf

[12] B. Gui, L. Dai, and L. J. Cimini, Jr., "OFDMA relaying and OFDM relaying for two-hop random network," in *Proc. of WCNC'08*.
http://www.eecis.udel.edu/~bgui/WCNC08_BO.pdf

[13] L. Zhang and L. J. Cimini, Jr., "Hop-by-hop routing strategy for multihop decode-and- forward cooperative networks," in *Proc. of WCNC'08*.
http://www.eecis.udel.edu/~lzhang/WCNC2008Final.pdf

[14] J. Yackoski, L. Zhang, B. Gui, C.-C. Shen, and L. J. Cimini, Jr., "Realistic evaluation of cooperative relaying networks using decentralized distributed space-time block coding," in *Proc. of*

ICC'08.

http://www.eecis.udel.edu/~lzhang/ICC2008Final.pdf

B. Journal Articles

[1] B. Gui and L. J. Cimini, Jr., "Bit loading algorithms for cooperative OFDM systems," *EURASIP Journal on Advances in Signal Processing,* 2008.

http://www.eecis.udel.edu/~bgui/eurasip_BL.pdf

[2] L. Zhang and L. J. Cimini, Jr., "Power-efficient relay-selection in cooperative networks using decentralized distributed space-time block coding," *EURASIP Journal on Advances in Signal Processing,* 2008.

http://www.eecis.udel.edu/~lzhang/EURASIPJournal.pdf

[3] B. Gui, L. Dai, and L. J. Cimini, Jr., "Routing strategies in multihop cooperative networks," to appear in *IEEE Transactions on Wireless Communications,* Feb. 2009.

http://www.eecis.udel.edu/~bgui/TWC_routing.pdf

[4] L. Zhang and L. J. Cimini, Jr., "Efficient power allocation for decentralized distributed space-time block coding," to appear *IEEE Transactions on Wireless Communications.*

http://www.eecis.udel.edu/~lzhang/TWirelessAccepted1.pdf

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http://www.cis.udel.edu/~yackoski/papers/cooppac_commag_draft.pdf

[6] B. Gui, L. Dai, and L. J. Cimini, Jr., "OFDMA relaying and OFDM relaying for two-hop random network," submitted to *IEEE Transactions on Wireless Communications.*

http://www.eecis.udel.edu/~bgui/TWC_OFDMA.pdf

[7] L. Zhang and L. J. Cimini, Jr., "Lifetime maximization for decode-and-forward cooperative networks," submitted to *IEEE Transactions on Wireless Communications.*

http://www.eecis.udel.edu/~lzhang/TwirelessSubmitted2.pdf

[8] L. Zhang and L. J. Cimini, Jr., "Performance of decentralized distributed space-time block coding for single or multiple sources," submitted to *IEEE Transactions on Wireless Communications.*

http://www.eecis.udel.edu/~lzhang/TWirelessSubmitted1.pdf

C. Dissertations

[1] B. Gui, *Cooperative OFDM Networking*, Ph.D. dissertation, ECE Dept., Univ. of Delaware, Fall 2008.

http://www.eecis.udel.edu/~bgui/Bgui_Dissertation.pdf

[2] J. Yackoski, *High Performance MAC Protocols for Decentralized Wireless Networks Using Local Coordination*, Ph.D. dissertation, CIS Dept., Univ. of Delaware, Spring 2009.

http:www.cis.udel.edu/~yackoski/papers/thesis_draft.pdf

6. Honors

The paper "Selective Relaying in OFDM Multihop Cooperative Networks" was chosen as the Best Paper in the PHY/MAC Track at the *IEEE WCNC 2007* conference, March 2007, Hong Kong.

7. *Transitions*

The research described here is still in the early stages of development. However, future tactical networks will be deployed in highly dynamic environments, with severe constraints on energy and bandwidth. The results of these investigations, based on the concept of cooperative networking, will have the most impact precisely in these applications. In particular, through cooperation, the average power used in the network (per node) can be significantly reduced, and the reliability and connectivity can be dramatically increased. The approach described here, the techniques devised, and the understanding obtained will be invaluable in meeting the objective of reliably communicating in highly dynamic environments. Our hope is that we might collaborate with Drs. John Matyjas and Mike Gans, AFRL, in the near future, to facilitate some transition of this work.